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MODELING MICROWAVE HEATING OF CERAMICS

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ABSTRACT

A method to simulate microwave heating of ceramics which has a temperature dependent dielectric property is developed here. In this simulation study, the impedance method is used to find the microwave energy absorbed by ceramics and a non-linear finite element method is used to determine the dynamic temperature profile in the ceramics during microwave heating. Using the developed method, the thermal runaway phenomenon in the microwave heating of ceramics is successfully simulated.With detailed analysis of the microwave energy absorption pattern in the ceramics, the effects of dielectric properties on microwave energy absorption by ceramics are discussed. The causes of non-uniform heating with microwave energy that has been observed in our laboratory are also investigated.

INTRODUCTION

The use of microwave energy is a new and exciting approach in ceramic processing. It has already been used in sintering, joining and melting of ceramics[1]. Since microwave heating is a volumetric process, it could provide uniform heating so that the temperature gradient which is observed in conventional rapid heating methods can be avoided. Rapid and uniform heating are important in the joining and sintering of ceramics. On the contrary, non-uniform heating is often observed in our laboratory with microwave sintering or joining. Therefore, it is of practical interest to simulate the phenomenon of microwave heating for better control and more efficient use. In spite of the significance of the problem, there is no comprehensive analysis available which would describe the behavior of ceramic materials exposed to electromagnetic radiation. Research by Iskander [2] and Watters et al. [3] has revealed some of the mechanisms of microwave heating of ceramics. However, the simulation of microwave heating of ceramics with a temperature dependent dielectric property is still lacking. In this paper, a method of simulating microwave heating of ceramics with temperature dependent dielectric properties is developed here. The impedance method is used to find the microwave

energy absorbed by ceramics. A non-linear finite element method is developed to determine the dynamic temperature profile in the ceramics during microwave heating. Using this developed method, the thermal runaway phenomenon in the microwave heating of ceramics is successfully simulated. With detailed analysis of the microwave energy absorption pattern in the ceramics, the effects of dielectric properties on microwave energy absorption by ceramics are discussed. The causes of non-uniform heating using microwave energy that has been observed in our laboratory are also investigated. In doing so, a better understanding of microwave heating of ceramics is realized.

THEORY

In order to simulate microwave heating of ceramics, it is necessary to find the electric and magnetic field strength inside ceramics and the absorbed microwave energy. Electric and magnetic fields are linked by Maxwell's equations, a group of linear differential equations. Assuming an $e^{-i\omega t}$ harmonic time dependence, Maxwell's equations can be expressed as follows,

$$\nabla \bullet (\varepsilon_0 \varepsilon_r E) = \rho_e \qquad (1)$$

$$\nabla \bullet (\mu_0 \mu_r H) = 0 \qquad (2)$$

$$\nabla \times E = j\,\omega \mu_0 \mu_r H \qquad (3)$$

$$\nabla \times H = \sigma E - j\,\omega \varepsilon_0 \varepsilon_r E \qquad (4)$$

where ε_0 and μ_0 are the permitivity and permeability in the vacuum, ε_r and μ_r are the relative permitivity and permeability of the material, σ is the conductivity of the material. E and H are the electric and magnetic field strength, respectively. The propagation of energy in the electromagnetic field can be deduced from this equation system and leads to Poynting's theorem

$$P = -\int_S [E \times H^*]\, d S \qquad (5)$$

which states that the mean energy, P, flowing into a surface, S, depends on the amplitude, distribution and prevailing phase of the electric and magnetic field.
By using Gauss' law, equation 5 can be converted into the volume integral which can then be resolved into three single integrals

$$P = j\omega \int_V \mu_0 \mu_r (H \bullet H^*)\, dv - j\omega \int_V \varepsilon_0 \varepsilon_r' (E \bullet E^*)\, dv$$

$$+ \omega \int_V \varepsilon_0 \varepsilon_r'' (E \bullet E^*)\, dv \qquad (6)$$

The first two integrals take account of the magnetic and electric fields respectively while the third represents the necessary dissipation in the dielectric in a general form. Therefore, the energy converted into heat by the alternating field is

$$P = \omega \varepsilon_0 \varepsilon_r'' \int_V (E \bullet E^*)\, dv \ (W) \qquad (7)$$

It increases according to the frequency, the square of the electric field strength and the imaginary part of the dielectric constant. Once the profile of ε'' as function of temperature and the electric field strength in the homogeneous body are known, it may be possible to study the thermal runaway conditions through the source-incorporated heat-diffusion equation. The diffusion of thermal energy in a homogeneous bound volume V is determined by the partial differential equation

$$\rho C_p \frac{\partial T}{\partial t} - K_h \nabla^2 T = p \qquad (8)$$

where ρ, C_p and K_h are the mass density, specific heat and thermal conductivity of the material, respectively. p is the microwave energy density absorbed by the material. At the boundary of the volume V, the boundary condition

$$K_h \mathbf{n} \bullet \nabla T = h(T - T_0) + \varepsilon \sigma_r (T^4 - T_0^4) \qquad (9)$$

must be satisfied, in which h is the heat convection coefficient, ε and σ_r are the emissivity of the material and Stefan-Boltzmann constant. T_0 is the ambient temperature. The initial condition is

$$T(r, 0) = T_i \qquad (10)$$

This heat diffusion equation is analogous to the forced Fisher equation

$$T_t = T_{xx} + G(T) \qquad (11)$$

which is known to have chaotic behavior for specific initial and boundary conditions as investigated by Fisher [4] in 1937 and Rothe [5] in 1981.

DESCRIPTION OF THE MODEL

For simplicity, a ceramic slab with finite thickness under plane wave radiation is considered here as depicted in figure 1. The incident electric field is a monochromatic plane wave propagating in the z-direction and is polarized along the x-axis. To account for material non-linearity during microwave heating, the slab is further divided into layers so that the finite element method can be used accurately. It is assumed that each element has the same material properties during the microwave heating process at each temperature step. Since the ceramic slab is assumed to be very large, the problem becomes one-dimensional. In the following discussion, layers with smaller thicknesses will be considered as different media since they may have different material properties such as dielectric constant and loss factor which are functions of temperature during the microwave heating process.

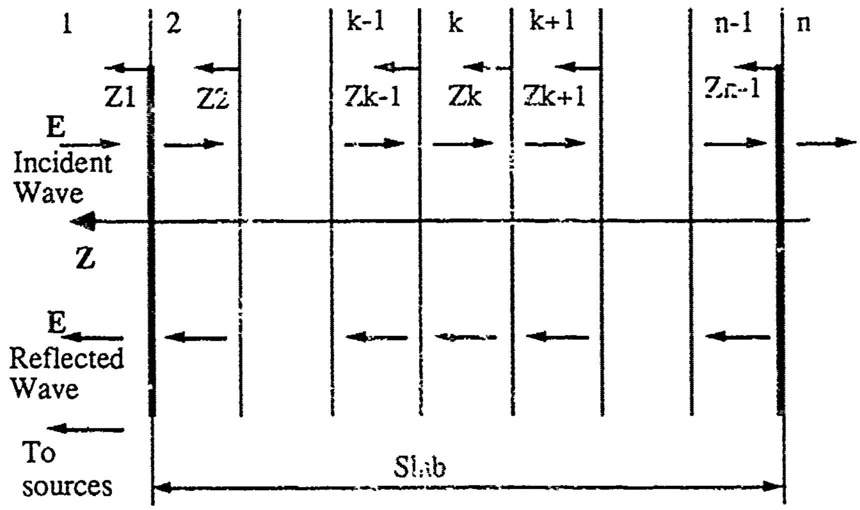


Figure 1. Ceramic Slab.

To simulate microwave heating of ceramics, the microwave energy absorbed by the ceramic slab must first be calculated. Therefore, the electric and magnetic fields in the ceramic slab have to be determined first. The electromagnetic field inside a dielectric body of arbitrary shape is difficult to determine. For the model considered here, an impedance method [6] is applied and proven to be effective to account for material non-linearity.

The application of the impedance method can be described as follows. When an electric field is incident on the ceramic slab, which is now assumed to be composed of several different layer, multiple reflection will occur in the different layers leading to positive and negative traveling waves. A generalized reflection coefficient is defined for any layer as the ratio of the incident and reflected field. Hence, the

total field can be represented by the positive traveling wave and the generalized reflection coefficient . In the first layer, the incident field is known and the reflected field is unknown. For the Nth layer, the generalized reflection coefficient is zero because there is no negative traveling wave The total field impedance, which is complex and position dependent, is defined as the ratio of electric field over the magnetic field. For the Nth layer, the total field impedance will be equal to the field impedance for that layer. At an interface, the total field impedances for adjacent layers are equal due to the field boundary condition at that interface. With this boundary condition, the total impedance at different interfaces can be found. Hence, the reflected field in the first layer is found. By using the boundary condition that the electric field is continuous at each interface, the electromagnetic field strength in each layer is readily found. The resulting field can then be used to calculate the microwave energy absorbed by that layer.

When the microwave energy absorbed by the slab is known, the heat diffusion equation can be used to calculate the temperature variation with time and position. Since the dielectric constant and loss factor are functions of temperature, the microwave energy absorbed by the ceramic slab is also a function of temperature. Hence, the heat diffusion equation becomes non-linear. A non-linear finite element method is therefore needed to find the dynamic temperature distribution profile. At the surface of the ceramic slab, radiation link elements are used to account for radiation heat loss. Conduction loss is neglected since the radiation loss is the prime heat loss at high temperature. The detailed implementation of the non-linear analysis is as follows. The time step to do the non-linear analysis is designated first. The temperature at the end of time step is then estimated. The material properties at the middle of the temperature increment are used for each media. The microwave energy absorbed by each media with different dielectric properties is calculated according to the technique described above. The temperature distribution is then obtained by using power absorption data. The computed results will be compared with the prior estimated temperature. Such an iteration procedure will continue until the difference between the estimated and calculated temperature reaches a prescribed value.

RESULTS AND DISCUSSION

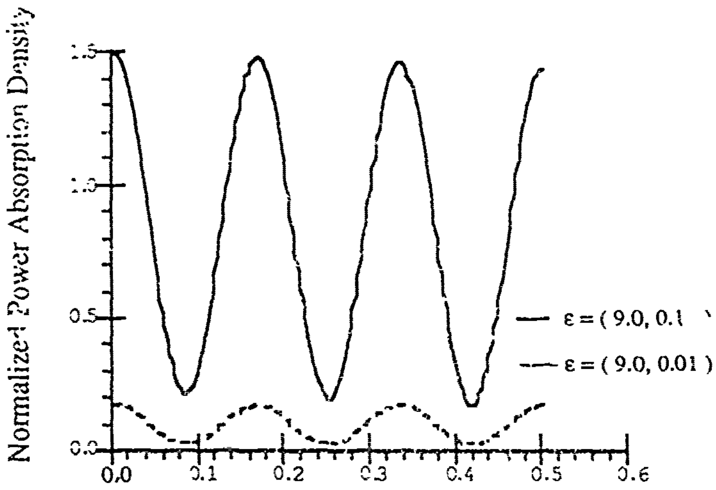
Microwave Energy Absorption by Ceramics

By using the technique stated above, the effects of the dielectric constant and the loss factor on the power absorption by ceramics are considered. Figure 2 gives the comparison of power absorption by ceramic slabs with the same dielectric constant and different loss factors. The increase in loss factor will dramatically increase the ability of the ceramic slab to absorb microwave energy. Figure 3 shows that with the increase of both dielectric constant and loss factor, the uniformity and ability of power absorption by ceramics are also increased.

Simulating Microwave Heating of Ceramics

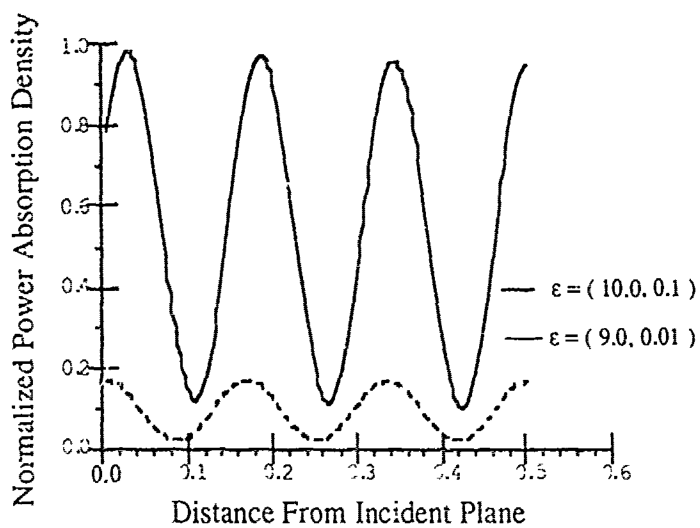
The developed non-linear finite element method is used in this case to find the dynamic temperature profile of a ceramic slab under plane wave radiation

considering changes in both the dielectric constant and the loss factor with temperature. The analysis procedure is displayed in figure 4. The data of dielectric constant and loss factor change with temperature are taken from Fukushima et al.[7]. The incident microwave power flux is 30kw/m^2. The microwave frequency is taken to be 6 GHz to be consistent with the dielectric data.



Distance From Incident Plane
(Incident Wavelength)

Figure 2. Microwave Power Absorption for Slabs with Different Loss Factors.



Distance From Incident Plane
(Incident Wavelength)

Figure 3.Microwave Power Absorption for Slabs with Different Dielectric Properties.

The mass density, specific heat and thermal conductivity are taken to be $4 g/cm^3$, $1.125 j/g\,^oC$ and $10 w/cm^2$, respectively. The thickness of the plate is taken to be 5.08 cm. The finite element analysis routine on ANSYS is implemented in the calculation. The calculation is done on a VAX-11/780 computer. The CPU time is 79 seconds.

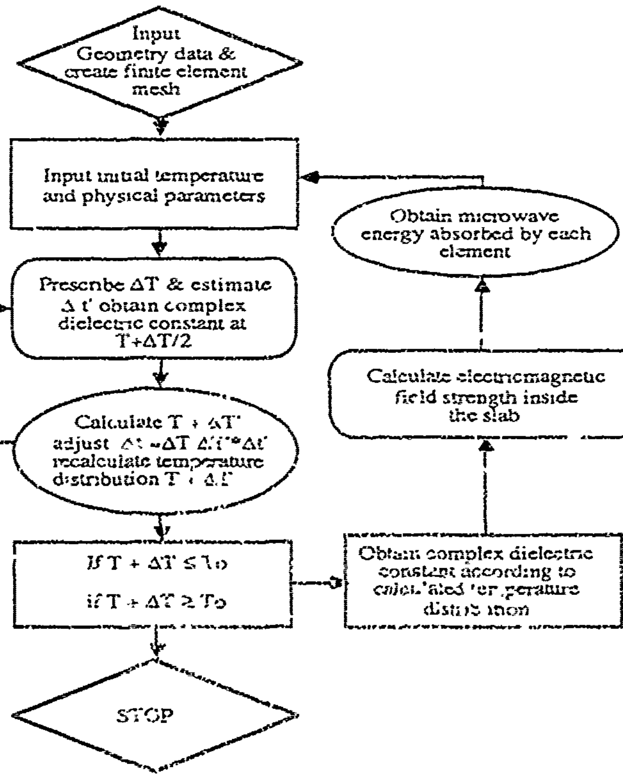


Figure 4. Procedures for Simulating Microwave Heating of Ceramics.

Figure 5 gives the temperature variation with time at 0.01m inside the slab from the microwave incident plane. The temperature increases slowly at the beginning and rapidly after 600°C.

Figure 6 displays the temperature profile over the thickness of the slab. An appreciable temperature gradient is observed. This temperature gradient is caused by non-symmetric microwave radiation of the ceramic slab and radiation heat loss at the boundary, which subsequently results in a non-uniform power absorption by the ceramic slab. If symmetric radiation is realized, i.e., microwave radiation is from both sides of the slab, the uneven heating will result from boundary radiation heat loss only and the center of slab will have the highest temperature. Hence, the radiation heat loss at the boundary is the main contribution to the non-uniform heating with microwaves observed in our laboratory where the ceramic sample is melted at the center while the boundary is still intact. In order to prevent this effect, good insulation must be used at the boundary. Also, in practice, the ceramic sample needs to be rotated continuously to prevent any uneven radiation. Figure 7 shows

the variation of total microwave energy absorbed by the ceramic slab verse the temperature variation at 0.01m inside the slab from microwave incident plane. It indicates that as the ceramic becomes hot, its energy absorption ability is increased. Therefore, thermal runaway is realized in microwave heating.

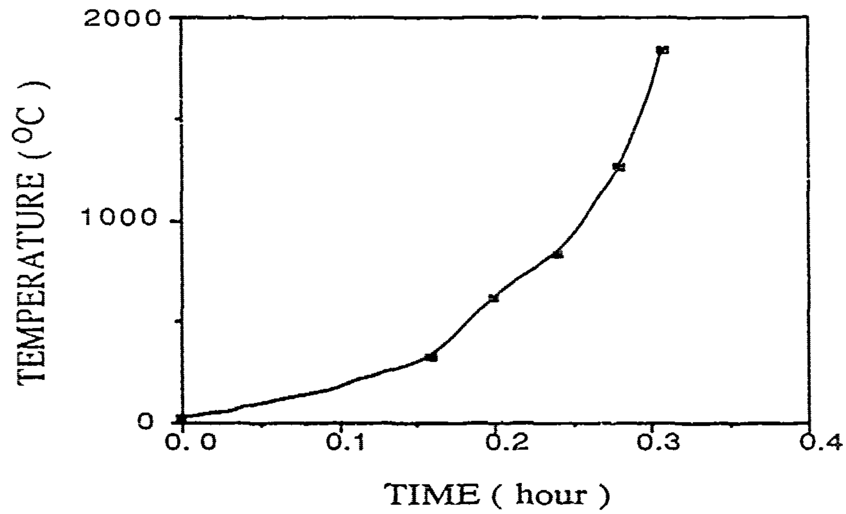


Figure 5. Dynamic Temperature Profile 0.01m inside the Slab from the Incident Plane.

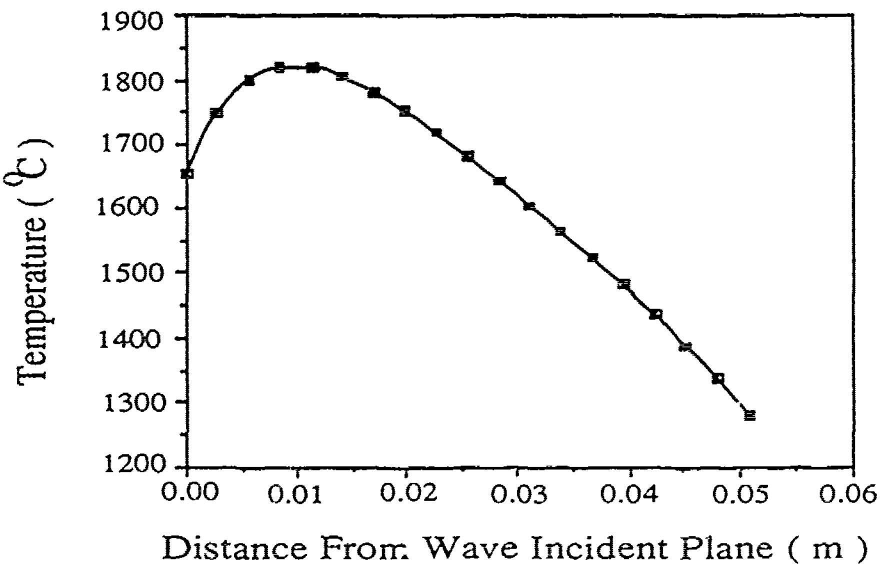


Figure 6. Temperature Distribution over the Thickness of the Slab.

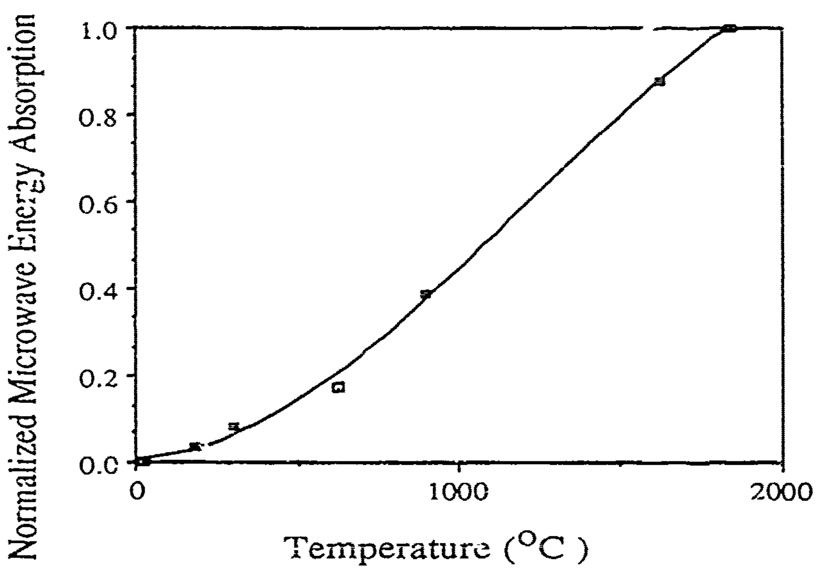


Figure 7. Total Microwave Energy Absorbed by slab vs. Temperature.

CONCLUSION

A method of modeling microwave heating of ceramics is developed here. The results show that increasing the dielectric constant could increase microwave power absorption uniformity while increasing the loss factor could increase the material's ability to absorb microwave energy. It is found that non-uniform heating observed in the laboratory can be caused by boundary radiation loss and non-uniform radiation by the microwave source. Through this research, it is observed that the dielectric property of a material at elevated temperature has a very important role in designing microwave processing technique. In microwave sintering of ceramics, the green sample changes its microstructure during microwave heating. Its dielectric properties change with not only temperature but also microstructure. Hence, the characterization of the dielectric property of ceramics during microwave sintering is very important . In doing so, we are not only able to control the sintering process but also able to understand thoroughly the mechanism of microwave sintering. Therefore, we need to develop a method to dynamically characterize the dielectric property of materials with temperatures as well as model microwave heating for the ceramic samples of complicated shapes.

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